US009531164B2

(12) **United States Patent**
Raring et al.

(10) **Patent No.: US 9,531,164 B2**
(45) **Date of Patent: Dec. 27, 2016**

(54) **OPTICAL DEVICE STRUCTURE USING GAN SUBSTRATES FOR LASER APPLICATIONS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/759,273**

(22) Filed: **Apr. 13, 2010**

(65) **Prior Publication Data**

US 2010/0316075 A1 Dec. 16, 2010

Related U.S. Application Data

(60) Provisional application No. 61/168,926, filed on Apr. 13, 2009, provisional application No. 61/243,502, filed on Sep. 17, 2009.

(51) **Int. Cl.**

H01S 5/02	(2006.01)
H01S 5/22	(2006.01)
H01L 21/02	(2006.01)
H01S 5/028	(2006.01)
H01S 5/20	(2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01S 5/2201*** (2013.01); *H01L 21/0254* (2013.01); *H01L 21/02389* (2013.01); *H01L 21/02433* (2013.01); *H01S 5/0202* (2013.01); *H01S 5/028* (2013.01); *H01S 5/0287* (2013.01); *H01S 5/2009* (2013.01); *H01S 5/3202* (2013.01); *H01S 5/32341* (2013.01)

(58) **Field of Classification Search**

CPC H01S 5/3202; H01S 5/0202; H01S 5/2201
USPC 372/44.011
See application file for complete search history.

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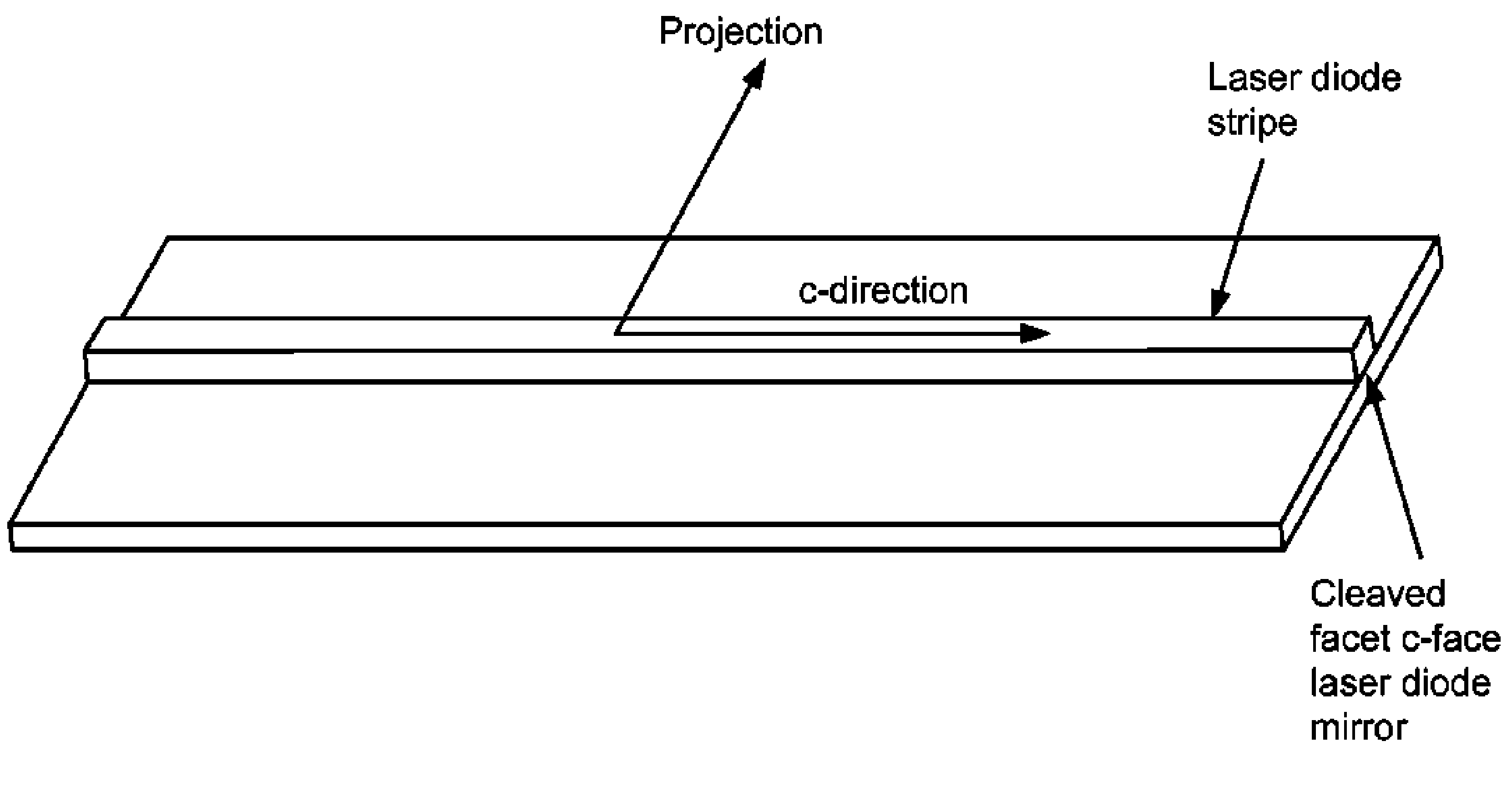
(57) **ABSTRACT**

An optical device includes a gallium nitride substrate member having an m-plane nonpolar crystalline surface region characterized by an orientation of about −2 degrees to about 2 degrees towards (000-1) and less than about 0.5 degrees towards (11-20). The device also has a laser stripe region formed overlying a portion of the m-plane nonpolar crystalline orientation surface region. A first cleaved c-face facet is provided on one end of the laser stripe region, and a second cleaved c-face facet is provided on the other end of the laser stripe region.

42 Claims, 12 Drawing Sheets

c-direction laser diode on nonpolar substrate with cleaved mirror



(51) **Int. Cl.**

H01S 5/32	(2006.01)
H01S 5/323	(2006.01)

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c-direction laser diode on nonpolar substrate with cleaved mirror

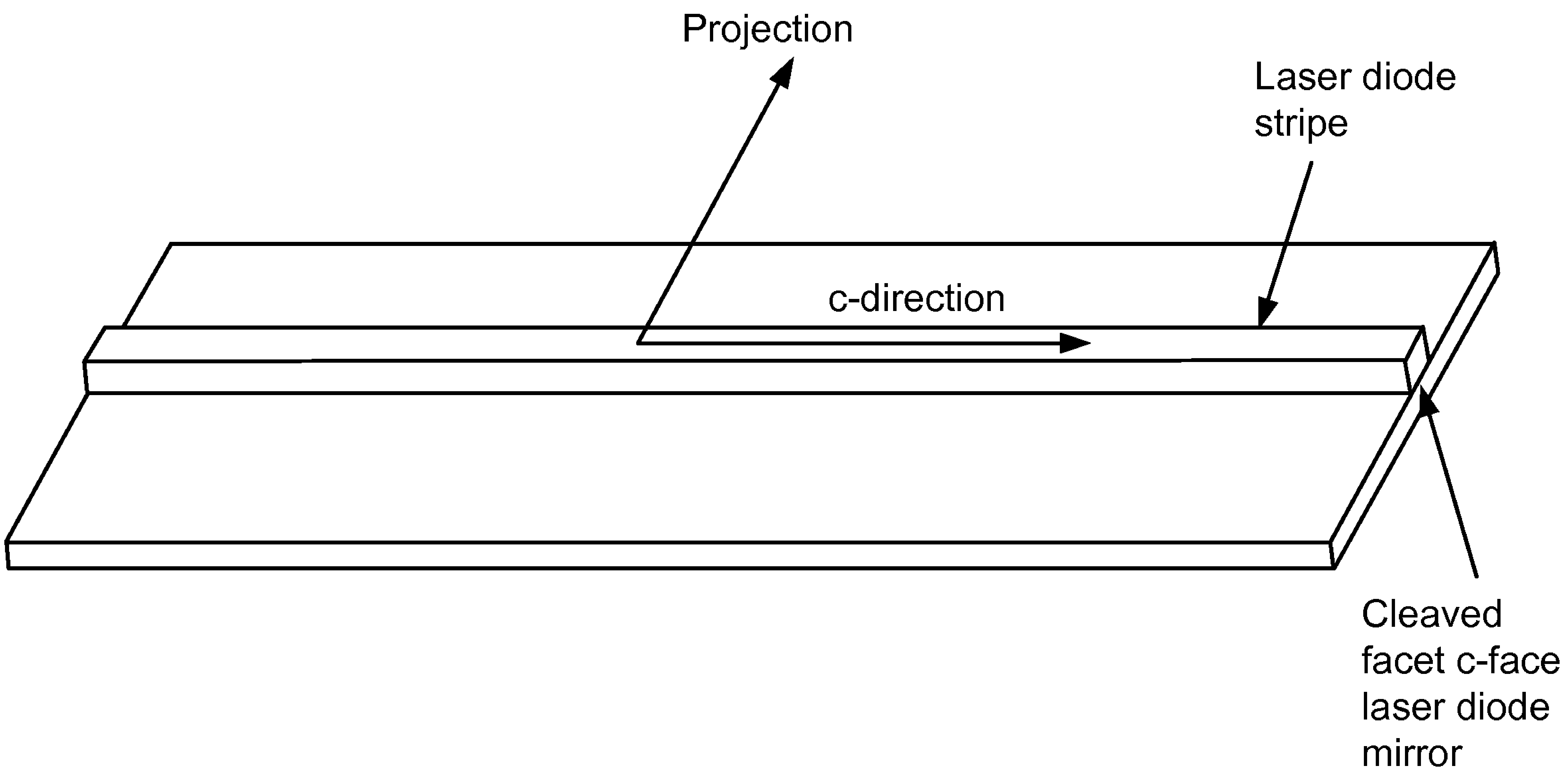


FIG. 1

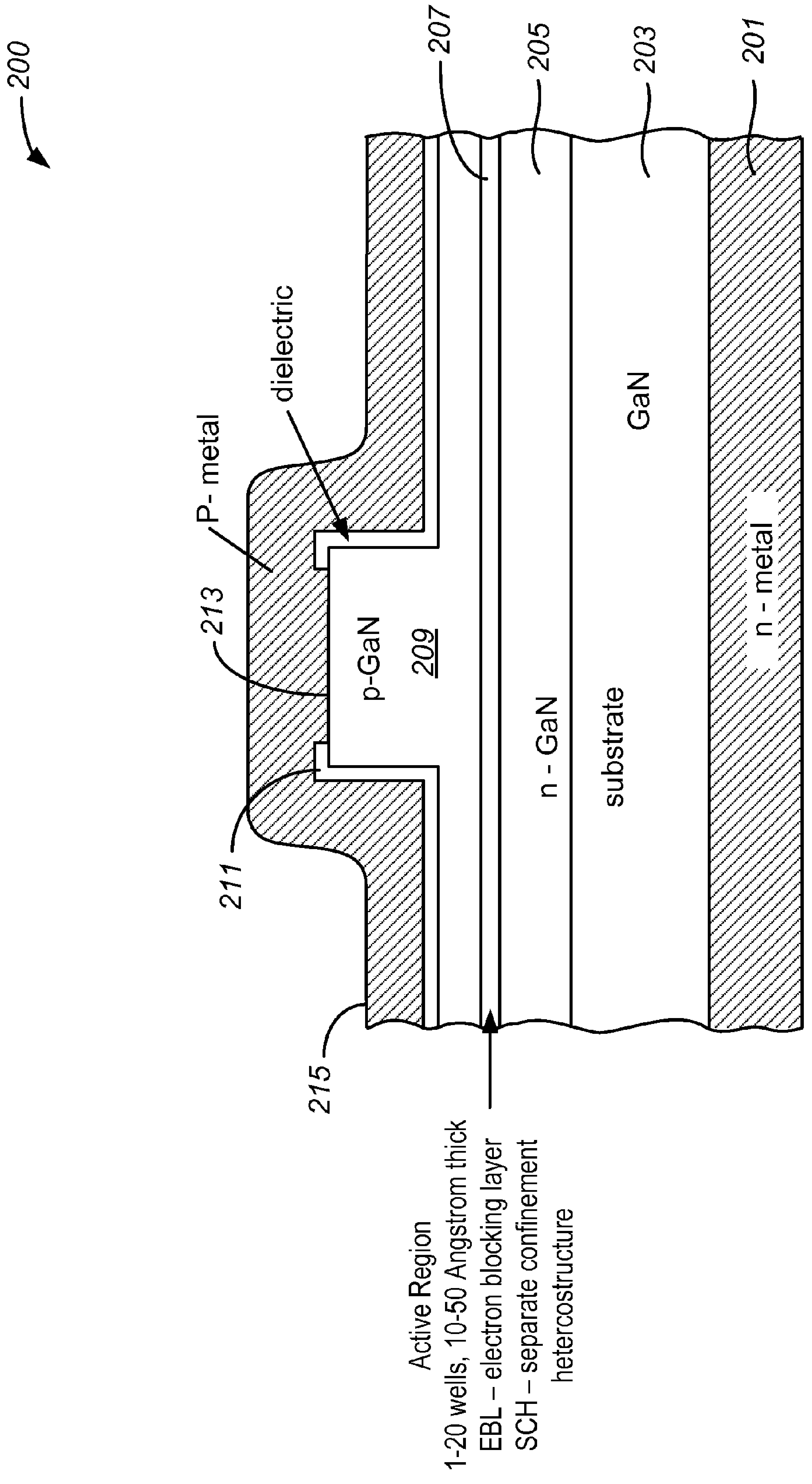
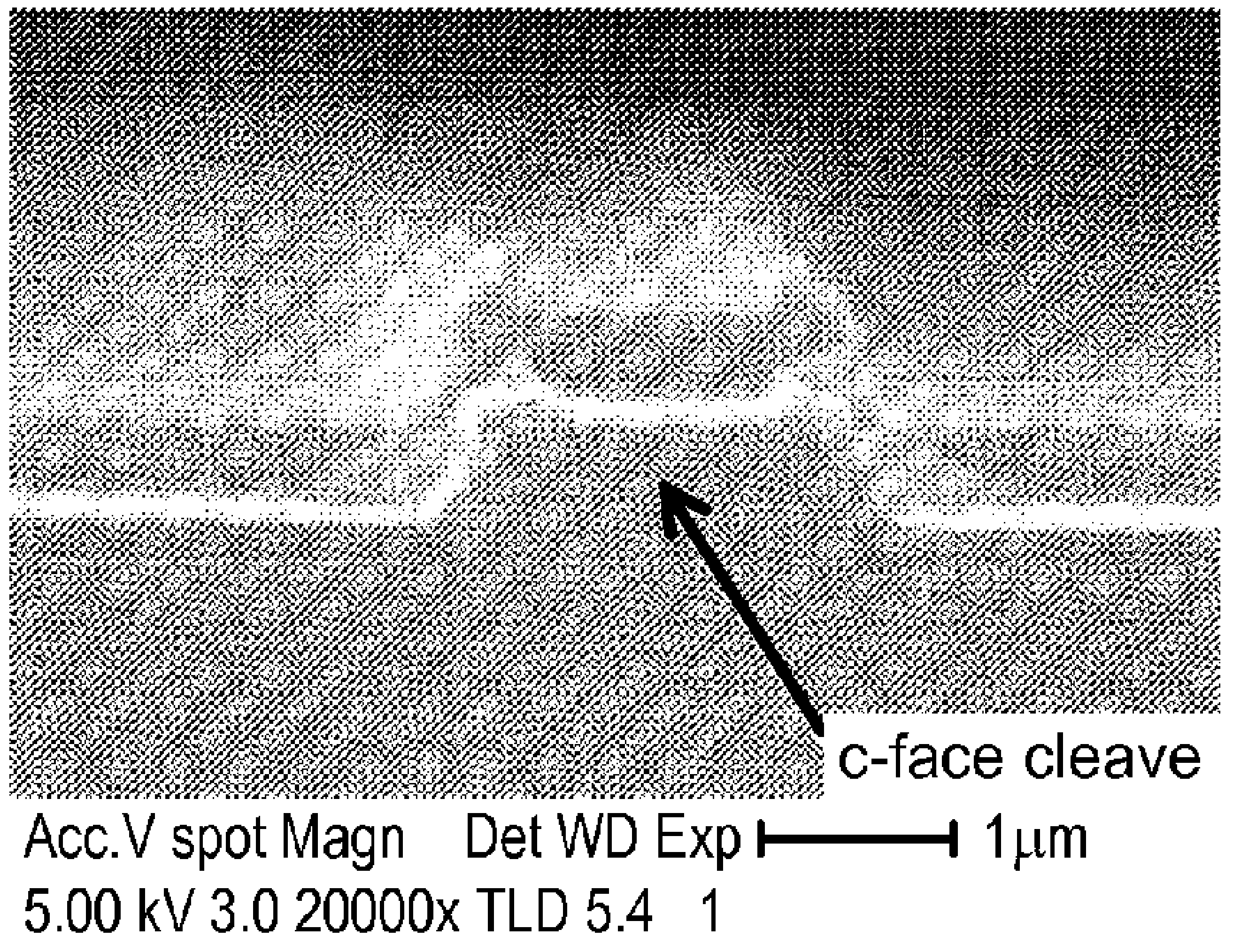

200
207
205
203
201
P- metal
dielectric
213
211
215
p-GaN
209
n - GaN
substrate
GaN
n - metal
Active Region
1-20 wells, 10-50 Angstrom thick
EBL – electron blocking layer
SCH – separate confinement
heterecostructure

FIG. 2

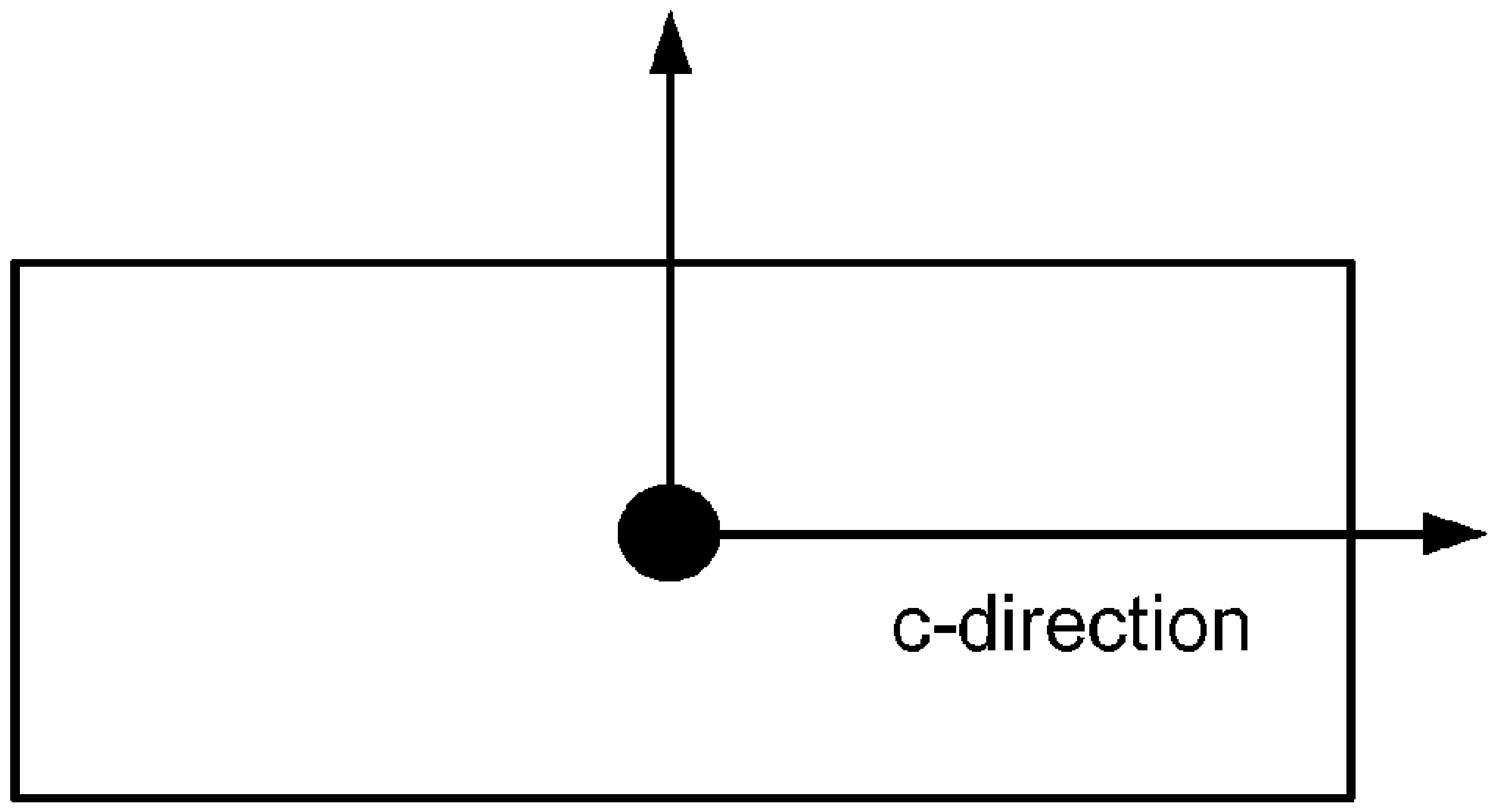
Mirrors/Polarization/Gain

- **c-direction cleaved facets**
  - Smooth and vertical = great mirror
- **Must orient laser in c-direction**
  - For max gain, light polarization must be perp. To laser stripe
- **Off-axis orientations to increase polarization/gain**



Projection

FIG. 3



M-plane Top View

FIG. 4

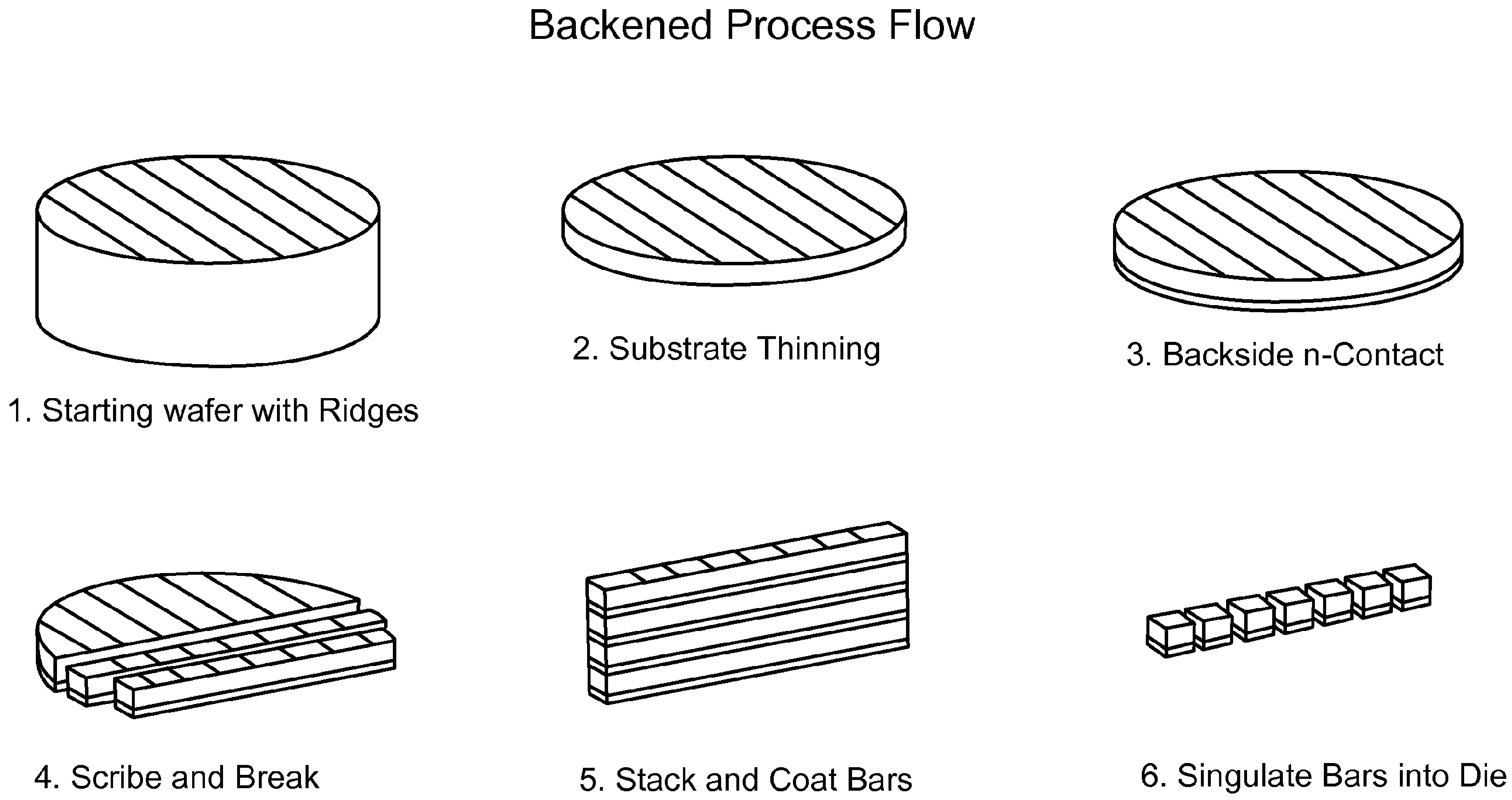
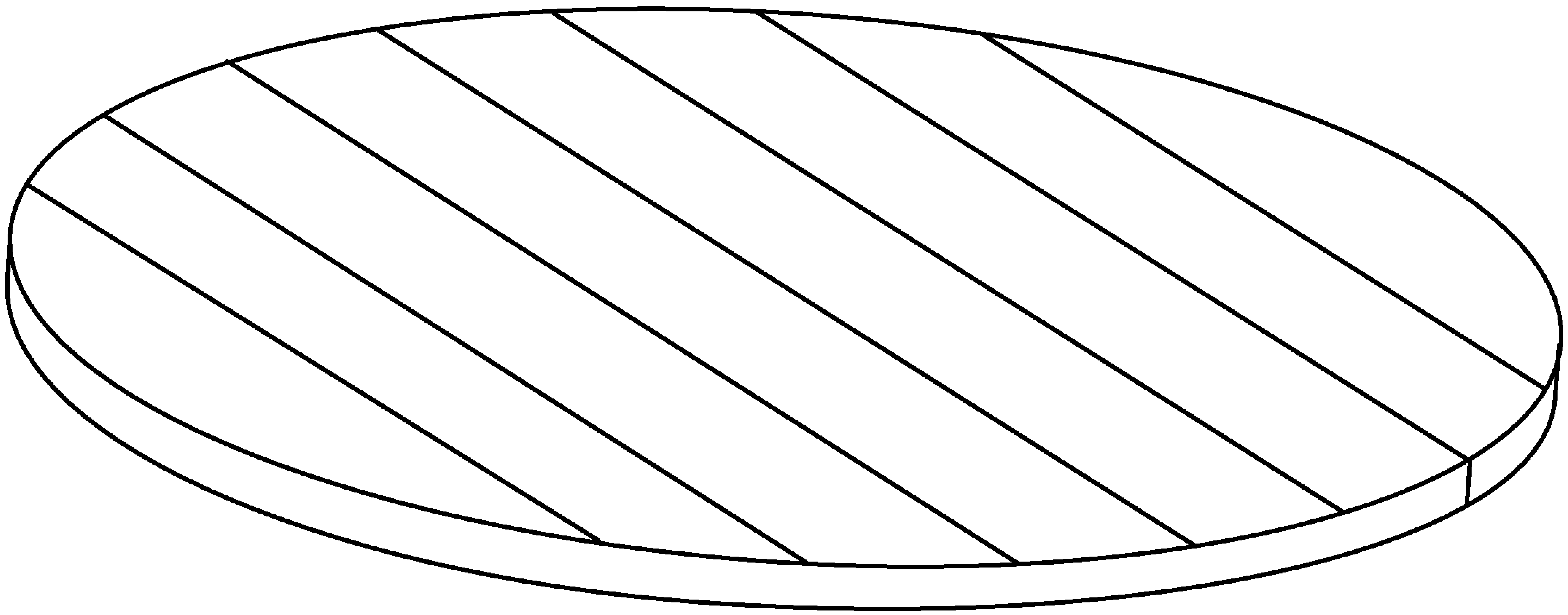

Backened Process Flow
1. Starting wafer with Ridges
2. Substrate Thinning
3. Backside n-Contact
4. Scribe and Break
5. Stack and Coat Bars
6. Singulate Bars into Die

FIG. 5



Substrate Thinning

FIG. 6

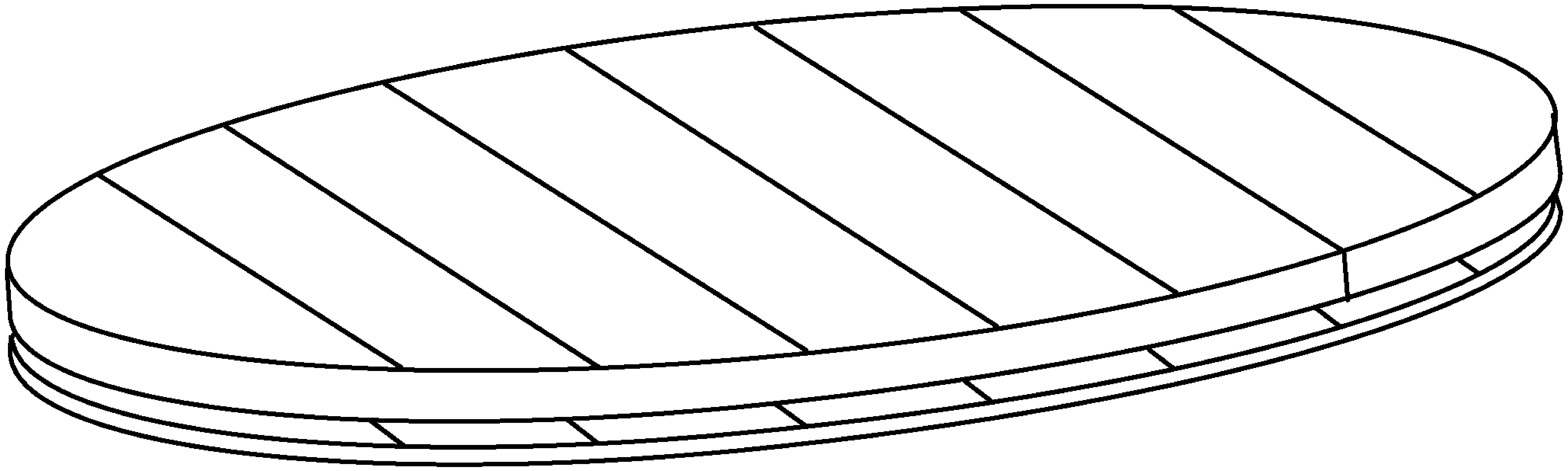
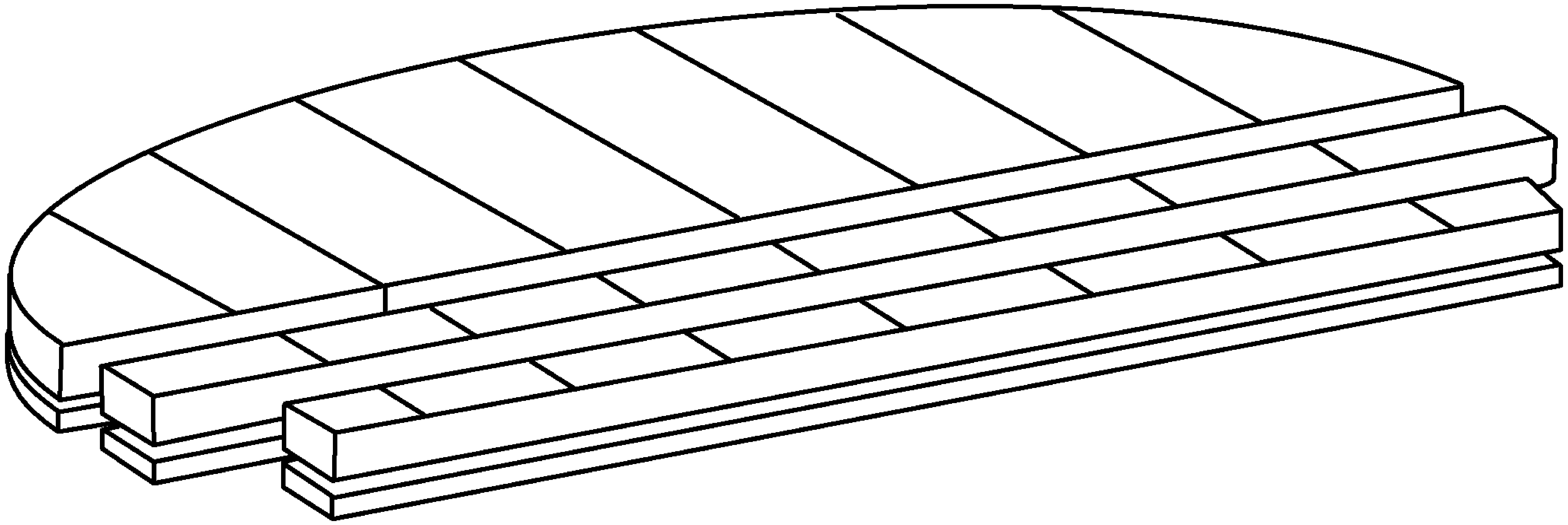
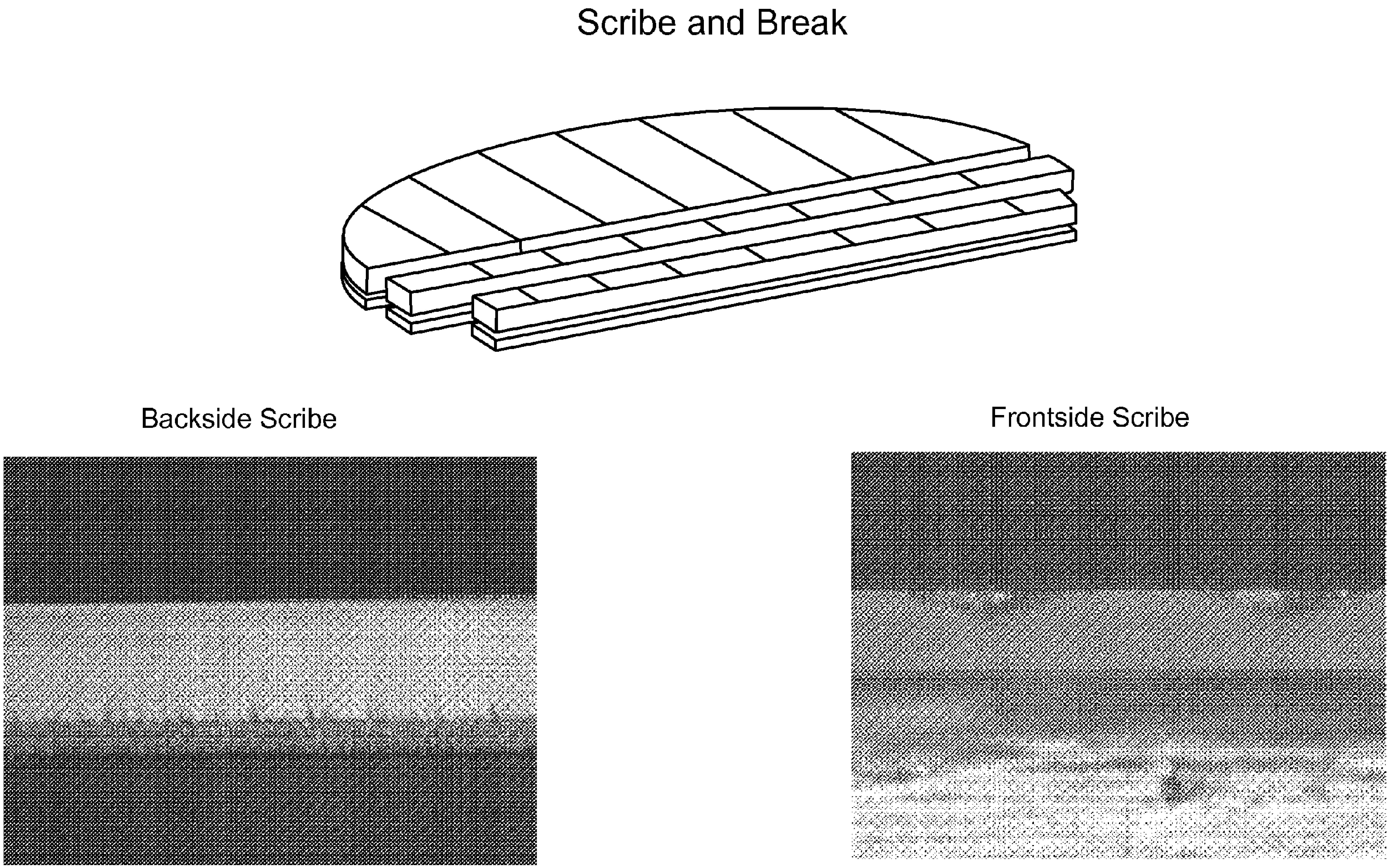


FIG. 7



Scribe and Break

FIG. 8



Scribe and Break

Backside Scribe

Frontside Scribe

FIG. 9

Scribe and Break

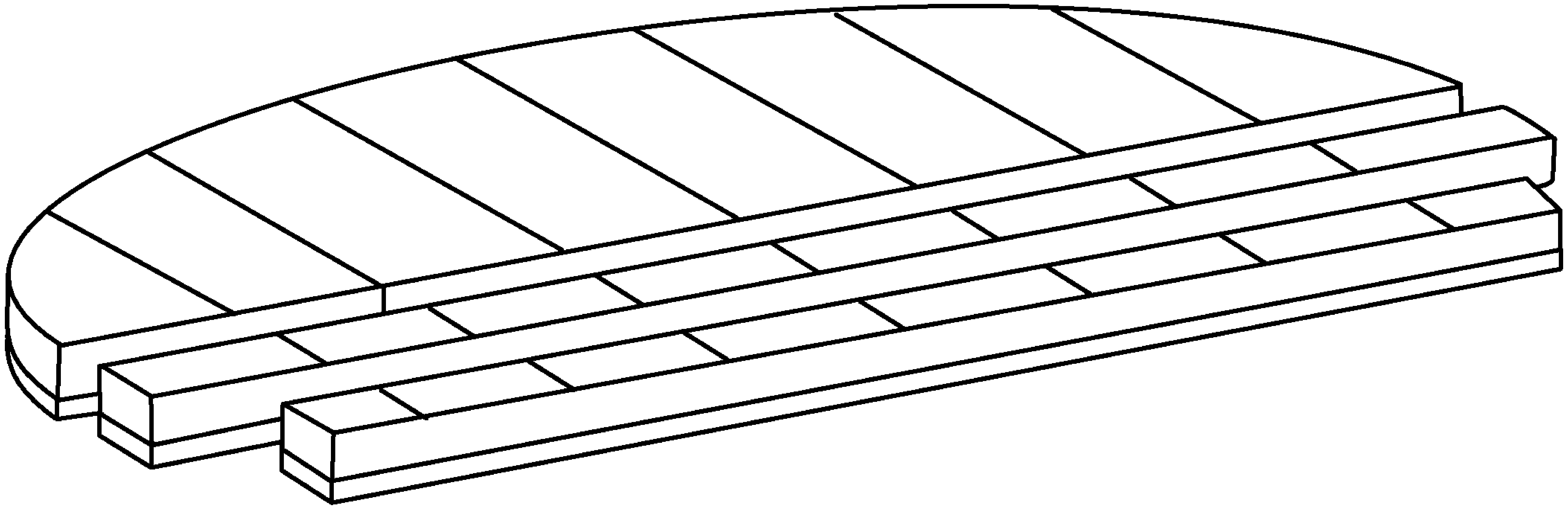
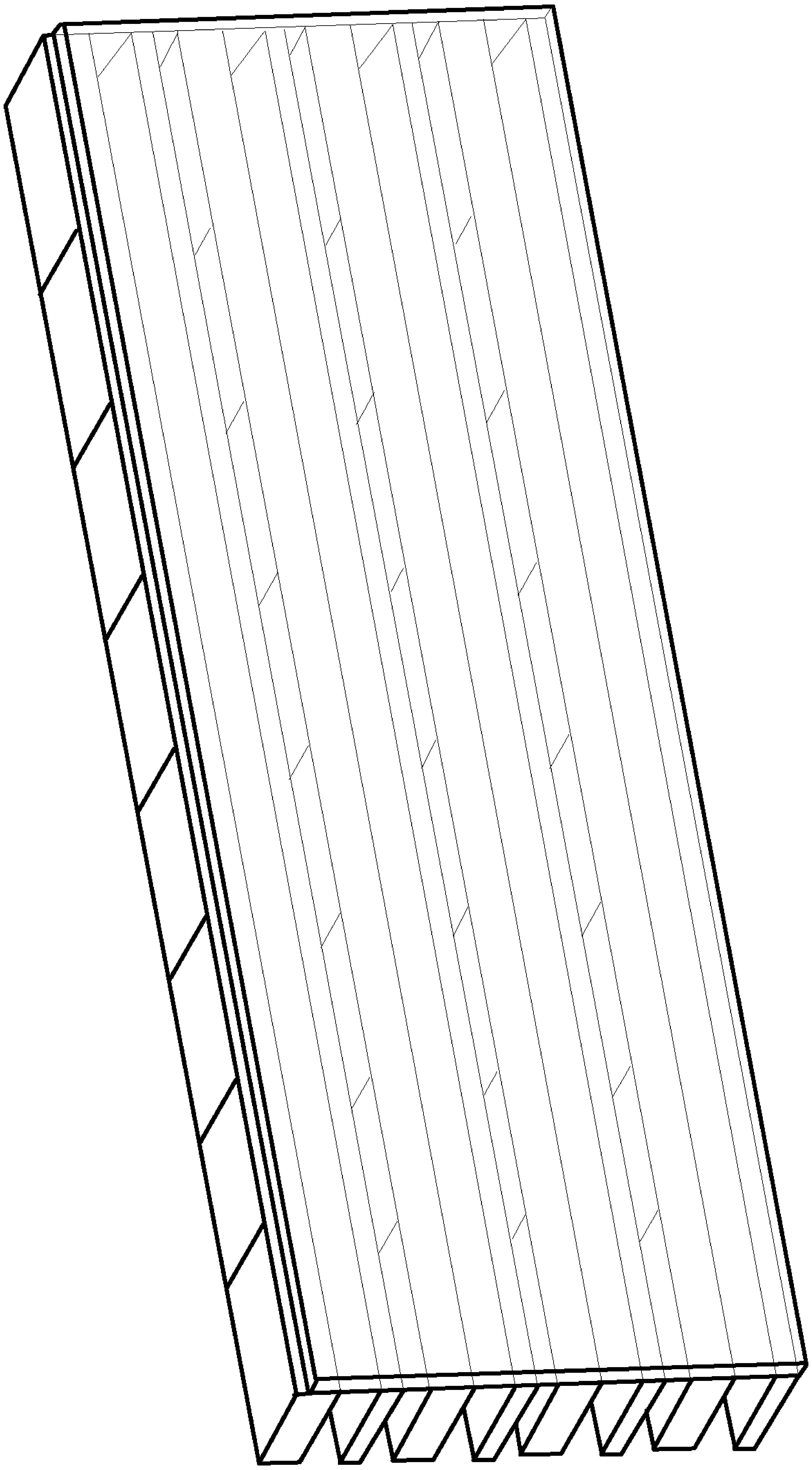


FIG. 10



Stack and Coat Bars

FIG. 11

Singulate Bars into Die

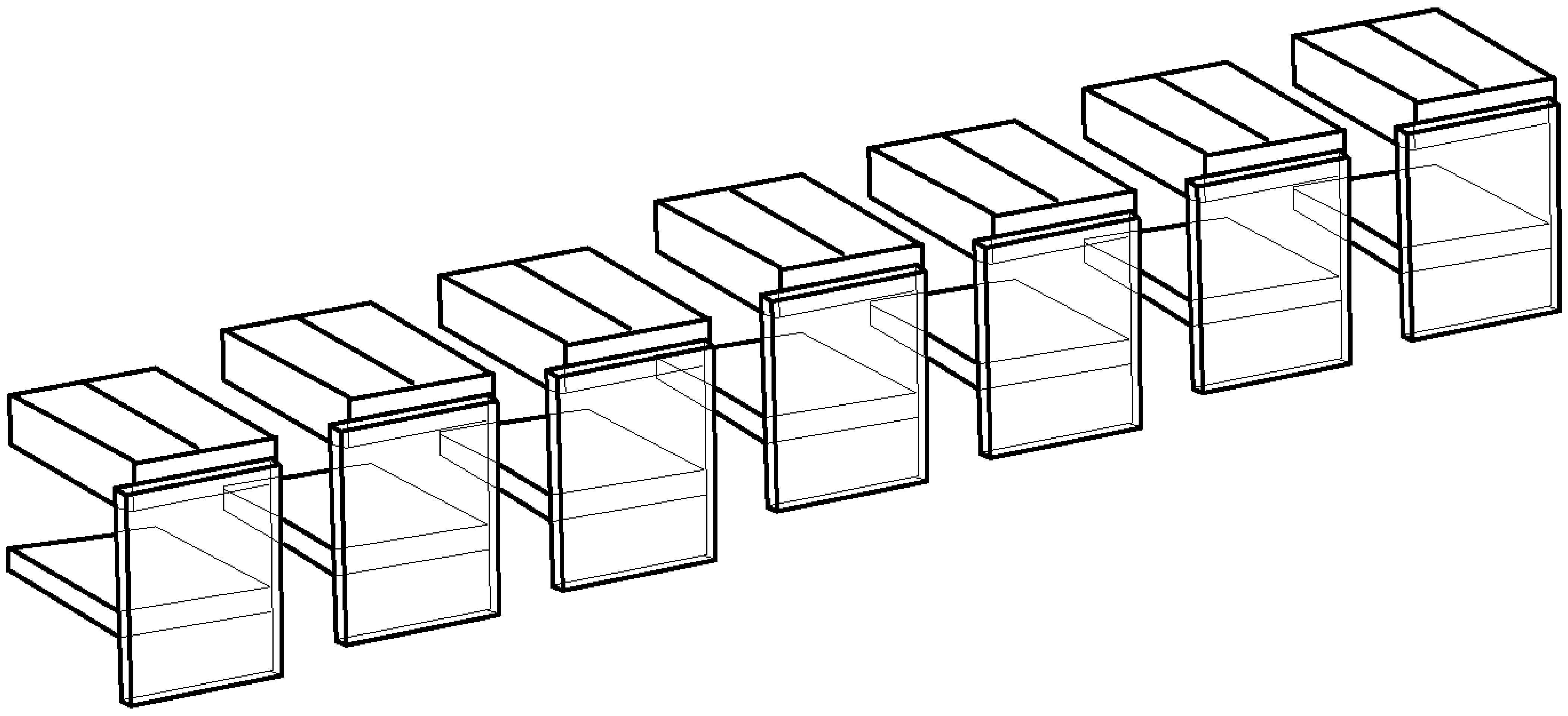
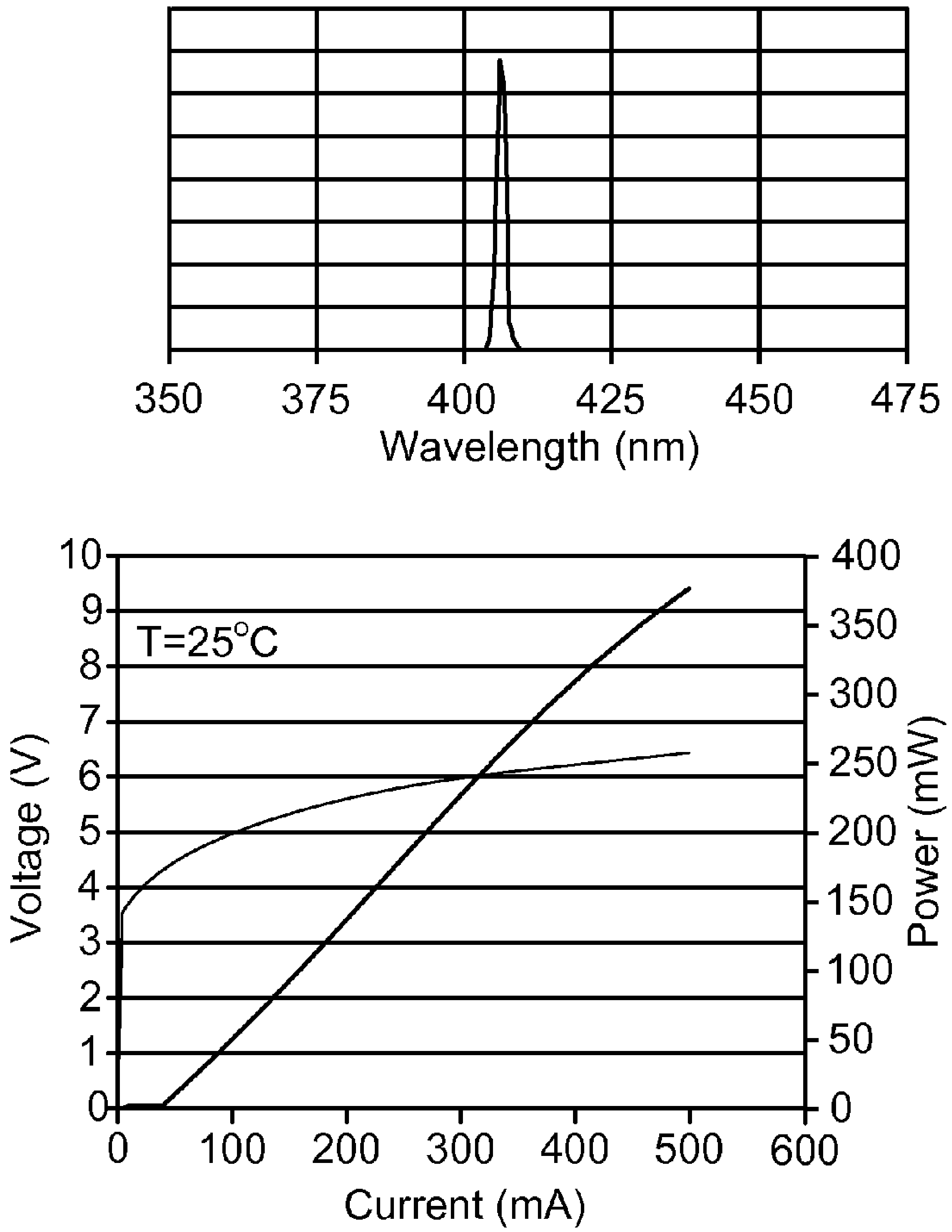


FIG. 12

405nm Laser Status

- Characteristics (CW)
  - $Power_{CW} > 350mW$
  - Kink-free operation
  - $I_{th} < 30mA$
  - $SE > 1.0$ W/A
  - Packaged on TO-56 header



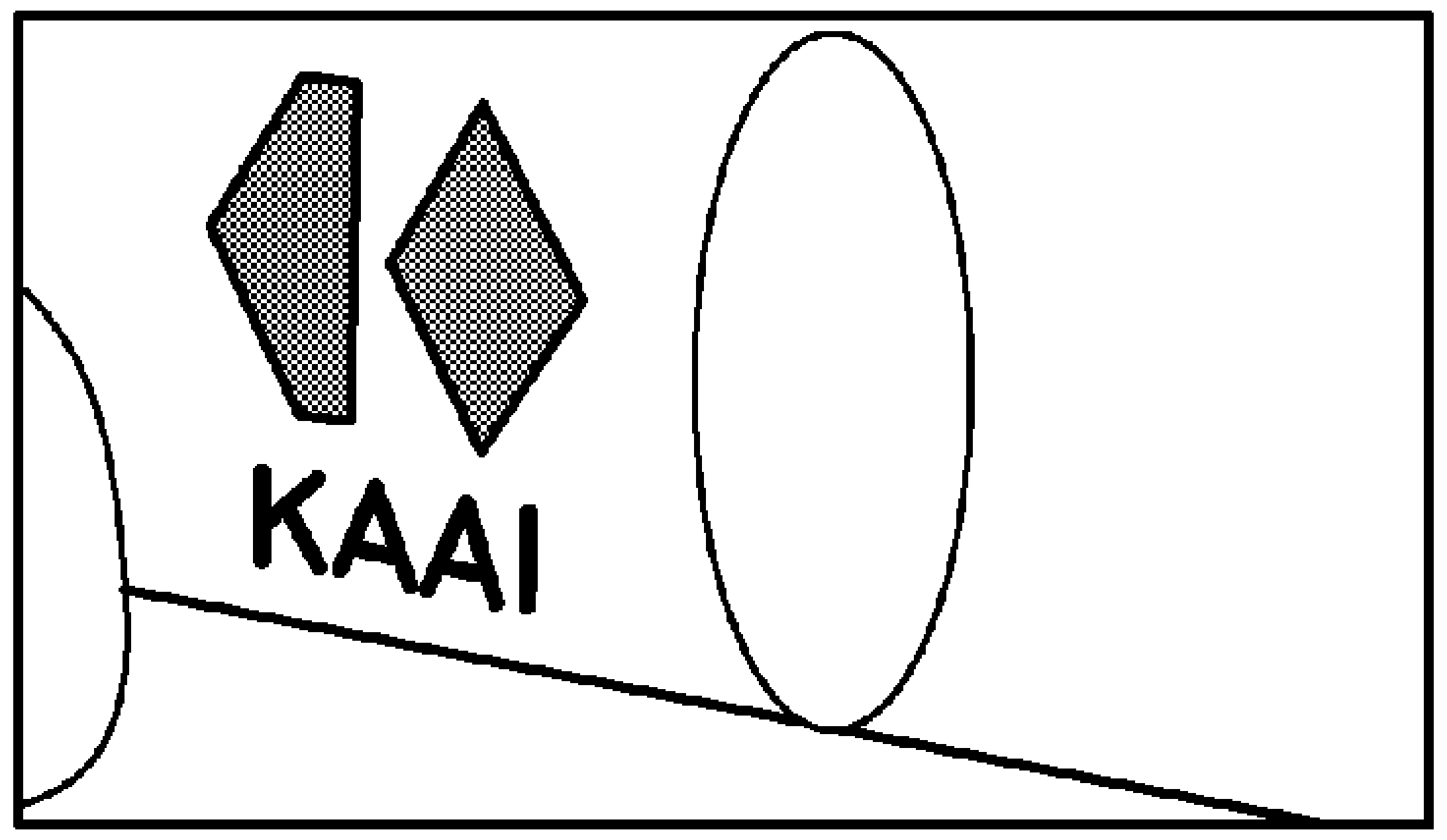


FIG. 13

OPTICAL DEVICE STRUCTURE USING GAN SUBSTRATES FOR LASER APPLICATIONS

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims priority to U.S. Ser. No. 61/168,926 filed Apr. 13, 2009, and U.S. Ser. No. 61/243,502 filed Sep. 17, 2009, each of which is commonly assigned and hereby incorporated by reference.

BACKGROUND OF THE INVENTION

This invention is directed to optical devices and related methods. More particularly, the present invention provides a method and device for emitting electromagnetic radiation using nonpolar gallium containing substrates such as GaN, MN, InN, InGaN, AlGaN, and AlInGaN, and others. Merely by way of example, the invention can be applied to optical devices, lasers, light emitting diodes, solar cells, photoelectrochemical water splitting and hydrogen generation, photodetectors, integrated circuits, and transistors, among other devices.

In the late 1800's, Thomas Edison invented the light bulb. The conventional light bulb, commonly called the "Edison bulb," has been used for over one hundred years for a variety of applications including lighting and displays. The conventional light bulb uses a tungsten filament enclosed in a glass bulb sealed in a base, which is screwed into a socket. The socket is coupled to an AC power or DC power source. The conventional light bulb can be found commonly in houses, buildings, and outdoor lightings, and other areas requiring light or displays. Unfortunately, drawbacks exist with the conventional Edison light bulb:

- The conventional light bulb is inefficient. More than 90% of the energy used for the conventional light bulb dissipates as thermal, rather than optical, energy.
- The conventional light bulb is not as reliable as it could be, often failing from thermal expansion and contraction of the filament element.
- Conventional light bulbs emit light over a broad spectrum, much of which does not result in bright illumination, and much of which is not perceived due to the spectral sensitivity of the human eye.
- Conventional light bulbs emit in all directions and are not ideal for applications requiring strong directionality or focus such as projection displays, optical data storage, or specialized directed lighting.

In 1960, the laser was first demonstrated by Theodore H. Maiman at Hughes Research Laboratories in Malibu. This laser utilized a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light at 694 nm. By 1964, blue and green laser output was demonstrated by William Bridges at Hughes Aircraft utilizing a gas laser design called an Argon ion laser. The Ar-ion laser utilized a noble gas as the active medium and produce laser light output in the UV, blue, and green wavelengths including 351 nm, 454.6 nm, 457.9 nm, 465.8 nm, 476.5 nm, 488.0 nm, 496.5 nm, 501.7 nm, 514.5 nm, and 528.7 nm. The Ar-ion laser had the benefit of producing highly directional and focusable light with a narrow spectral output, but the efficiency, size, weight, and cost of the lasers were undesirable.

As laser technology evolved, more efficient lamp pumped solid state laser designs were developed for the red and infrared wavelengths, but these technologies remained a challenge for blue and green lasers and blue lasers. As a result, lamp pumped solid state lasers were developed in the infrared, and the output wavelength was converted to the visible using specialty crystals with nonlinear optical properties. A green lamp pumped solid state lasers had 3 stages: electricity powers lamp, lamp excites gain crystal which lases at 1064 nm, 1064 nm goes into frequency conversion crystal which converts to visible 532 nm. The resulting green and blue lasers were called "lamp pumped solid state lasers with second harmonic generation" (LPSS with SHG) and were more efficient than Ar-ion gas lasers, but were still too inefficient, large, expensive, fragile for broad deployment outside of specialty scientific and medical applications. Additionally, the gain crystal used in the solid state lasers typically had energy storage properties which made the lasers difficult to modulate at high speeds, thereby limiting broader deployment.

To improve the efficiency of these visible lasers, high power diode (or semiconductor) lasers were utilized. These "diode pumped solid state lasers with SHG" (DPSS with SHG) had 3 stages: electricity powers 808 nm diode laser, 808 nm excites gain crystal which lases at 1064 nm, 1064 nm goes into frequency conversion crystal which converts to visible 532 nm. The DPSS laser technology extended the life and improved the efficiency of the LPSS lasers, and further commercialization ensue into more high end specialty industrial, medical, and scientific applications. The change to diode pumping, however, increased the system cost and required précised temperature controls, leaving the laser with substantial size and power consumption. Yet the technology did not address the energy storage properties, making the lasers difficult to modulate at high speeds.

As high power laser diodes evolved and new specialty SHG crystals were developed, it became possible to directly convert the output of the infrared diode laser to produce blue and green laser light output. These "directly doubled diode lasers" or SHG diode lasers had 2 stages: electricity powers 1064 nm semiconductor laser, 1064 nm goes into frequency conversion crystal which converts to visible 532 nm green light. These lasers designs are meant to improve the efficiency, cost and size compared to DPSS-SHG lasers, but the specialty diodes and crystals required make this challenging. Additionally, while the diode-SHG lasers have the benefit of being directly modulated, they suffer from severe sensitivity to temperature, limiting their application.

BRIEF SUMMARY OF THE INVENTION

This invention provides techniques related generally to optical devices. More particularly, the invention provides a method and device for emitting electromagnetic radiation using nonpolar or semipolar gallium containing substrates such as GaN, MN, InN, InGaN, AlGaN, and AlInGaN, and others. In specific embodiments, the electromagnetic radiation has wavelengths of 405, 450, 485, 500, 520, nanometers. The invention can be applied to optical devices, lasers, light emitting diodes, solar cells, photoelectrochemical water splitting and hydrogen generation, photodetectors, integrated circuits, and transistors, among other devices.

In a specific embodiment, an optical device is provided which includes a gallium nitride substrate member having an m-plane nonpolar crystalline surface region characterized by an orientation of about −2 degrees to about 2 degrees towards (000-1) and less than about 0.5 degrees towards (11-20). The crystalline surface can be characterized as a miscut and does not include a cut orientation of zero degrees. The device also has a laser stripe region formed overlying a portion of the m-plane nonpolar crystalline orientation surface region. In a preferred embodiment, the laser stripe region is characterized by a cavity orientation that is substantially parallel to the c-direction, the laser strip region having a first end and a second end. The device includes a first cleaved c-face facet provided on the first end of the laser stripe region. The first cleaved c-face facet preferably includes a laser scribed region. The device also has a second cleaved c-face facet provided on the second end of the laser stripe region. In a specific embodiment, the second cleaved c-face facet is also characterized by including a laser scribed region.

In some embodiments, the optical device includes a gallium nitride substrate member having an m-plane nonpolar crystalline surface region characterized by an orientation of about −17 degrees to about 17 degrees towards a c-plane. The crystalline surface can be characterized as a miscut and does not include a cut orientation of zero degrees. The device also has a laser stripe region formed overlying a portion of the m-plane nonpolar crystalline orientation surface region or alternatively the semi-polar crystalline orientation surface region. In a preferred embodiment, the laser stripe region has a first end and a second end. The device includes a first cleaved face facet provided on the first end of the laser stripe region. In a specific embodiment, the first cleaved face facet is characterized by a laser scribed region. The device also has a second cleaved face facet provided on the second end of the laser stripe region. In a specific embodiment, the second cleaved face facet is characterized by a laser scribed region.

In an alternative specific embodiment, the present invention provides a method for forming an optical device. The method includes providing a gallium nitride substrate member having an m-plane nonpolar crystalline surface region characterized by an orientation of about −2 degrees to about 2 degrees towards (000-1) and less than about 0.5 degrees towards (11-20). In a specific embodiment, the crystalline surface can be characterized as a miscut and does not include a cut orientation of zero degrees. The device also has a laser stripe region formed overlying a portion of the m-plane nonpolar crystalline orientation surface region. The method includes forming a laser stripe region overlying a portion of the m-plane nonpolar crystalline orientation surface region. In a specific embodiment, the laser stripe region is characterized by a cavity orientation substantially parallel to the c-direction. In a specific embodiment, the laser strip region has a first end and a second end. The method preferably forms a pair of cleaved facets including a first cleaved c-face facet provided on the first end of the laser stripe region and a second cleaved c-face facet provided on the second end of the laser stripe region.

In other embodiments, the present invention includes a device and method configured on other gallium and nitrogen containing substrate orientations. In a specific embodiment, the gallium and nitrogen containing substrate is configured on a family of planes including a {20-21} crystal orientation. In a specific embodiment, {20-21} is 14.9 degrees off of the m-plane towards the c-plane (0001). As an example, the miscut or off-cut angle is +/−17 degrees from the m-plane towards c-plane or alternatively at about the {20-21} crystal orientation plane. As another example, the present device includes a laser stripe oriented in a projection of the c-direction, which is perpendicular to the a-direction (or alternatively on the m-plane, it is configured in the c-direction). In one or more embodiments, the cleaved facet would be the gallium and nitrogen containing face (e.g., GaN face) that is +/−5 degrees from a direction orthogonal to the projection of the c-direction (or alternatively, for the m-plane laser, it is the c-face). Of course, there can be other variations, modifications, and alternatives.

In yet other embodiments, the present invention provides a laser diode device. The laser diode device is provided on a crystal plane that is oriented between −8 degrees and 8 degrees from {20-21} towards the c-plane according to one or more embodiments. In one or more embodiments, the surface orientation of the crystal plane can be miscut from +/−5 degrees towards the a-plane. In a specific embodiment, the laser cavity is oriented in the projection of the c-direction and also uses cleaved facet mirrors. Depending upon the embodiment, the laser diode is operable in the 390-410 nm, 410-430 nm, 430-450 nm, 450-480 nm, 480-510 nm, 510-540 nm, 540-600 nm range, and other ranges. In other embodiments, the present method and structure can also be applied to light emitting diode devices, commonly known as LEDs or the like. Of course, there can be other variations, modifications, and alternatives.

Benefits are achieved over pre-existing techniques using the present invention. In particular, the present invention enables a cost-effective optical device for laser applications. In a specific embodiment, the present optical device can be manufactured in a relatively simple and cost effective manner. Depending upon the embodiment, the present apparatus and method can be manufactured using conventional materials and/or methods according to one of ordinary skill in the art. The present laser device uses a nonpolar gallium nitride material capable of achieve a laser having a wavelength of about 400 nanometers and 405 nanometers can greater, among others. In other embodiments, the device and method can achieve a wavelength of about 500 nanometers and greater including 520 nanometers. Depending upon the embodiment, one or more of these benefits may be achieved. These and other benefits may be described throughout the present specification and more particularly below.

The present invention achieves these benefits and others in the context of known process technology. However, a further understanding of the nature and advantages of the present invention may be realized by reference to the latter portions of the specification and attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified perspective view of a laser device fabricated on a nonpolar substrate according to an embodiment of the present invention;

FIG. **2** is a detailed cross-sectional view of a laser device fabricated on a nonpolar substrate according to an embodiment of the present invention;

FIG. **3** is a cross-sectional view photograph of an c-direction cleaved facet for a laser device according to an embodiment of the present invention.

FIG. **4** is a top-view diagram of a laser device according to an embodiment of the present invention.

FIGS. **5** to **12** illustrate a simplified backend processing method of a laser device according to one or more embodiments of the present invention; and

FIG. **13** is a simplified diagram illustrating a laser device according to one or more examples of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

According to the present invention, techniques related generally to optical devices are provided. More particularly, the present invention provides a method and device for emitting electromagnetic radiation using non-polar or semipolar gallium containing substrates such as GaN, MN, InN, InGaN, AlGaN, and AlInGaN, and others. Merely by way of example, the invention can be applied to optical devices, lasers, light emitting diodes, solar cells, photoelectrochemical water splitting and hydrogen generation, photodetectors, integrated circuits, and transistors, among other devices.

FIG. **1** is a simplified perspective view of a laser device **100** fabricated on a non-polar substrate according to an embodiment of the present invention. This diagram is merely an example, which should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. As shown, the optical device includes a gallium nitride substrate member **101** having a nonpolar crystalline surface region characterized by an orientation of about −2 degrees to about 2 degrees towards (000-1) and less than about 0.5 degrees towards (11-20). In a specific embodiment, the gallium nitride substrate member is a bulk GaN substrate characterized by having a nonpolar crystalline surface region, but can be others. In a specific embodiment, the bulk nitride GaN substrate comprises nitrogen and has a surface dislocation density below 10^5 cm^{-2}. The nitride crystal or wafer may comprise $Al_xIn_yGa_{1-x-y}N$, where $0 \leq x, y, x+y \leq 1$. In one specific embodiment, the nitride crystal comprises GaN. In one or more embodiments, the GaN substrate has threading dislocations, at a concentration between about 10^5 cm^{-2} and about 10^8 cm^{-2}, in a direction that is substantially orthogonal or oblique with respect to the surface. As a consequence of the orthogonal or oblique orientation of the dislocations, the surface dislocation density is below about 10^5 cm^{-2}.

In a specific embodiment, the device has a laser stripe region formed overlying a portion of the nonpolar crystalline orientation surface region. In a specific embodiment, the laser stripe region is characterized by a cavity orientation is substantially parallel to the c-direction. In a specific embodiment, the laser strip region has a first end **107** and a second end **109**.

In a preferred embodiment, the device has a first cleaved c-face facet provided on the first end of the laser stripe region and a second cleaved c-face facet provided on the second end of the laser stripe region. In one or more embodiments, the first cleaved c-facet is substantially parallel with the second cleaved c-facet. Mirror surfaces are formed on each of the cleaved surfaces. The first cleaved c-facet comprises a first mirror surface. In a preferred embodiment, the first mirror surface is provided by a scribing and breaking process. The scribing process can use any suitable techniques, such as a diamond scribe or laser scribe or combinations. In a specific embodiment, the first mirror surface comprises a reflective coating. The reflective coating is selected from silicon dioxide, hafnia, and titaniatantalum pentoxidezirconia, including combinations, and the like. Depending upon the embodiment, the first mirror surface can also comprise an anti-reflective coating. Of course, there can be other variations, modifications, and alternatives.

Also in a preferred embodiment, the second cleaved c-facet comprises a second mirror surface. The second mirror surface is provided by a scribing and breaking process according to a specific embodiment. Preferably, the scribing is diamond scribed or laser scribed or the like. In a specific embodiment, the second mirror surface comprises a reflective coating, such as silicon dioxide, hafnia, titania, tantalum, pentoxide, zirconia, combinations, and the like. In a specific embodiment, the second mirror surface comprises an anti-reflective coating. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the laser stripe has a length and width. The length ranges from about 50 microns to about 3000 microns. The strip also has a width ranging from about 0.5 microns to about 50 microns, but can be other dimensions. In a specific embodiment, the width is substantially constant in dimension, although there may be slight variations. The width and length are often formed using a masking and etching process, which are commonly used in the art. Further details of the present device can be found throughout the present specification and more particularly below.

In a specific embodiment, the device is also characterized by a spontaneously emitted light is polarized in substantially perpendicular to the c-direction. That is, the device performs as a laser or the like. In a preferred embodiment, the spontaneously emitted light is characterized by a polarization ratio of greater than 0.1 to about 1 perpendicular to the c-direction. In a preferred embodiment, the spontaneously emitted light characterized by a wavelength ranging from about 405 nanometers to yield a blue emission, a green emission, and others. In a preferred embodiment, the spontaneously emitted light is highly polarized and is characterized by a polarization ratio of greater than 0.4. Of course, there can be other variations, modifications, and alternatives. Further details of the laser device can be found throughout the present specification and more particularly below.

FIG. **2** is a detailed cross-sectional view of a laser device **200** fabricated on a nonpolar substrate according to an embodiment of the present invention. This diagram is merely an example, which should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. As shown, the laser device includes gallium nitride substrate **203**, which has an underlying n-type metal back contact region **201**. In a specific embodiment, the metal back contact region is made of a suitable material such as those noted below and others. Further details of the contact region can be found throughout the present specification and more particularly below.

In a specific embodiment, the device also has an overlying n-type gallium nitride layer **205**, an active region **207**, and an overlying p-type gallium nitride layer structured as a laser stripe region **209**. In a specific embodiment, each of these regions is formed using at least an epitaxial deposition technique of metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), or other epitaxial growth techniques suitable for GaN growth. In a specific embodiment, the epitaxial layer is a high quality epitaxial layer overlying the n-type gallium nitride layer. In some embodiments the high quality layer is doped, for example, with Si or O to form n-type material, with a dopant concentration between about 10^{16} cm^{-3} and 10^{20} cm^{-3}.

In a specific embodiment, an n-type $Al_uIn_vGa_{1-u-v}N$ layer, where $0 \leq u, v, u+v \leq 1$, is deposited on the substrate. In a specific embodiment, the carrier concentration may lie in the range between about 10^{16} cm^{-3} and 10^{20} cm^{-3}. The deposition may be performed using metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). Of course, there can be other variations, modifications, and alternatives.

As an example, the bulk GaN substrate is placed on a susceptor in an MOCVD reactor. After closing, evacuating, and back-filling the reactor (or using a load lock configuration) to atmospheric pressure, the susceptor is heated to a temperature between about 1000 and about 1200 degrees

Celsius in the presence of a nitrogen-containing gas. In one specific embodiment, the susceptor is heated to approximately 1100 degrees Celsius under flowing ammonia. A flow of a gallium-containing metalorganic precursor, such as trimethylgallium (TMG) or triethylgallium (TEG) is initiated, in a carrier gas, at a total rate between approximately 1 and 50 standard cubic centimeters per minute (sccm). The carrier gas may comprise hydrogen, helium, nitrogen, or argon. The ratio of the flow rate of the group V precursor (ammonia) to that of the group III precursor (trimethylgallium, triethylgallium, trimethylindium, trimethylaluminum) during growth is between about 2000 and about 12000. A flow of disilane in a carrier gas, with a total flow rate of between about 0.1 and 10 sccm is initiated.

In a specific embodiment, the laser stripe region is made of the p-type gallium nitride layer **209**. In a specific embodiment, the laser stripe is provided by an etching process selected from dry etching or wet etching. In a preferred embodiment, the etching process is dry, but can be others. As an example, the dry etching process is an inductively coupled process using chlorine bearing species or a reactive ion etching process using similar chemistries. Again as an example, the chlorine bearing species are commonly derived from chlorine gas or the like. The device also has an overlying dielectric region, which exposes **213** contact region. In a specific embodiment, the dielectric region is an oxide such as silicon dioxide or silicon nitride, but can be others. The contact region is coupled to an overlying metal layer **215**. The overlying metal layer is a multilayered structure containing gold and platinum (Pt/Au), but can be others. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the laser device has active region **207**. The active region can include one to twenty quantum well regions according to one or more embodiments. As an example following deposition of the n-type $Al_uIn_vGa_{1-u-v}N$ layer for a predetermined period of time, so as to achieve a predetermined thickness, an active layer is deposited. The active layer may comprise a single quantum well or a multiple quantum well, with 1-20 quantum wells. The quantum wells may comprise InGaN wells and GaN barrier layers. In other embodiments, the well layers and barrier layers comprise $Al_wIn_xGa_{1-w-x}N$ and $Al_yIn_zGa_{1-y-z}N$, respectively, where $0 \leq w, x, y, z, w+x, y+z \leq 1$, where $w<u$, y and/or $x>v$, z so that the bandgap of the well layer(s) is less than that of the barrier layer(s) and the n-type layer. The well layers and barrier layers may each have a thickness between about 1 nm and about 40 nm. In another embodiment, the active layer comprises a double heterostructure, with an InGaN or $Al_wIn_xGa_{1-w-x}N$ layer about 10 nm to 100 nm thick surrounded by GaN or $Al_yIn_zGa_{1-y-z}N$ layers, where $w<u$, y and/or $x>v$, z. The composition and structure of the active layer are chosen to provide light emission at a preselected wavelength. The active layer may be left undoped (or unintentionally doped) or may be doped n-type or p-type. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the active region can also include an electron blocking region, and a separate confinement heterostructure. In some embodiments, an electron blocking layer is preferably deposited. The electron-blocking layer may comprise $Al_sIn_tGa_{1-s-t}N$, where $0 \leq s, t, s+t \leq 1$, with a higher bandgap than the active layer, and may be doped p-type. In one specific embodiment, the electron blocking layer comprises AlGaN. In another embodiment, the electron blocking layer comprises an AlGaN/GaN superlattice structure, comprising alternating layers of AlGaN and GaN, each with a thickness between about 0.2 nm and about 5 nm. Of course, there can be other variations, modifications, and alternatives.

As noted, the p-type gallium nitride structure, which can be a p-type doped $Al_qIn_rGa_{1-q-r}N$, where $0 \leq q, r, q+r \leq 1$, layer is deposited above the active layer. The p-type layer may be doped with Mg, to a level between about 10^{16} cm^{-3} and 10^{22} cm^{-3}, and may have a thickness between about 5 nm and about 1000 nm. The outermost 1-50 nm of the p-type layer may be doped more heavily than the rest of the layer, so as to enable an improved electrical contact. In a specific embodiment, the laser stripe is provided by an etching process selected from dry etching or wet etching. In a preferred embodiment, the etching process is dry, but can be others. The device also has an overlying dielectric region, which exposes 213 contact region. In a specific embodiment, the dielectric region is an oxide such as silicon dioxide, but can be others. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the metal contact is made of suitable material. The reflective electrical contact may comprise at least one of silver, gold, aluminum, nickel, platinum, rhodium, palladium, chromium, or the like. The electrical contact may be deposited by thermal evaporation, electron beam evaporation, electroplating, sputtering, or another suitable technique. In a preferred embodiment, the electrical contact serves as a p-type electrode for the optical device. In another embodiment, the electrical contact serves as an n-type electrode for the optical device. Of course, there can be other variations, modifications, and alternatives. Further details of the cleaved facets can be found throughout the present specification and more particularly below.

FIG. **3** is a cross-sectional view photograph of a c-direction cleaved facet for a laser device according to an embodiment of the present invention. This diagram is merely an example, which should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. As shown, the c-direction cleaved facet is smooth and provides a suitable mirror surface. Details of the top-view of the laser device are provided below.

FIG. **4** is a top-view diagram of a laser device according to an embodiment of the present invention. This diagram is merely an example, which should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. As shown, the laser stripe is configured in the c-direction, which has a projection normal to the c-direction. As shown, the top-view of the gallium nitride substrate is of a slight mis-cut or off-cut surface region orientation according to a specific embodiment.

A method of processing a laser device according to one or more embodiments may be outline as follows, see also FIG. **5**:

1. Start;
2. Provide processed substrate including laser devices with ridges;
3. Thin substrate from backside;
4. Form backside n-contact;
5. Scribe pattern for separation of the laser devices configured in bar structures;
6. Break scribed pattern to form a plurality of bar structures;
7. Stack bar structures;
8. Coat bars structures;
9. Singulate bar structures into individual dies having laser device; and
10. Perform other steps as desired.

The above sequence of steps is used to form individual laser devices on a die from a substrate structure according to one or more embodiments of the present invention. In one or more preferred embodiments, the method includes cleaved facets substantially parallel to each other and facing each other in a ridge laser device configured on a non-polar gallium nitride substrate material. Depending upon the embodiment, one or more of these steps can be combined, or removed, or other steps may be added without departing from the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. Further details of this method are provided throughout the present specification and more particularly below.

FIG. **6** is a simplified illustrating of a substrate thinning process according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. In a specific embodiment, the method begins with a gallium nitride substrate material including laser devices and preferably ridge laser devices, but can be others. The substrate has been subjected to frontside processing according to a specific embodiment. After frontside processing has been completed, one or more of the GaN substrates are mounted onto a sapphire carrier wafer or other suitable member. As an example, the method uses Crystalbond 509, which is a conventional mounting thermoplastic. The thermoplastic can be dissolved in acetone or other suitable solvent. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the carrier wafer is mounted to a lapping jig. An example of such lapping jig is made by Logitech Ltd. of the United Kingdom, or other vendor. The lapping jig helps maintain planarity of the substrates during the lapping process according to a specific embodiment. As an example, the starting thickness of the substrates are ~325 um+/−20 um, but can be others. In a specific embodiment, the method laps or thins the substrates down to 70-80 um thickness, but can also be thinner or slightly thicker. In a preferred embodiment, the lapping jig is configured with a lapping plate, which is often made of a suitable material such as cast iron configured with a flatness of less than 5 um, but can be others. Preferably, the method uses a lapping slurry that is 1 part silicon carbide (SiC) and 10 parts water, but can also be other variations. In a specific embodiment, the SiC grit is about 5 um in dimension. In one or more embodiments, the lapping plate speed is suitable at about 10 revolutions per minute. Additionally, the method can adjust the lapping jig's down pressure to achieve a desired lapping rate, such as 2-3 um/min or greater or slightly less according to one or more embodiments.

In a specific embodiment, the present method includes a lapping process that may produce subsurface damage in the GaN material to cause generation of mid level traps or the like. The midlevel traps may lead to contacts having a Schottky characteristic. Accordingly, the present method includes one or more polishing processes such that ~10 um of material having the damage is removed according to a specific embodiment. As an example, the method uses a Politex™ polishing pad of Rohm and Haas, but can be others, that is glued onto a stainless steel plate. A polishing solution is Ultraso1300 K manufactured by Eminess Technologies, but can be others. The Ultra-Sol 300 K is a high-purity colloidal silica slurry with a specially designed alkaline dispersion. It contains 70 nm colloidal silica and has a pH of 10.6. The solids content is 30% (by weight). In a specific embodiment, the lapping plate speed is 70 rpm and the full weight of the lapping jig is applied. In a preferred embodiment, the method includes a polishing rate of about ~2 um/hour, but can be others. Of course, there can be other variations, modifications, and alternatives.

In other embodiments, the present invention provides a method for achieving high quality n-type contacts for m-plane GaN substrate material. In a specific embodiment, the method provides contacts that are rough to achieve suitable ohmic contact. In a specific embodiment, the roughness causes exposure of other crystal planes, which lead to good contacts. In a preferred embodiment, the present method includes a lapped surface, which is rough in texture to expose more than one or multiple different crystal planes. In other embodiments, lapping may be followed by etching such as dry etching and/or wet etching. In a specific embodiment, etching removes the subsurface damage, however, it is likely not to planarize the surface like polishing. Of course, there can be other variations, modifications, and alternatives.

FIG. **7** is a simplified diagram illustrating a backside n-contact method according to one or more embodiments. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. After the thinning process is complete, the method forms n-contacts on the backside of the substrates according to one or more embodiments. At this point, the thinned substrates are still mounted to and maintained on the sapphire wafer. In a preferred embodiment, the thinned substrates are "batch process" for efficiency and handling. In a specific embodiment, the method using batch processing helps prevent any damage associated with handling very thin (60-80 um) substrates.

As an example, the backside contact includes about 300 Å Al/3000 Å Au or other suitable materials. In a specific embodiment, the contact is a stack of metals that are deposited by e-beam evaporation or other suitable techniques. In a preferred embodiment and prior to the metal stack deposition, the method includes use of a wet etch such as an hydrofluoric acid wet etch to remove any oxides on the surface. In a specific embodiment, the metal stack is preferably not annealed or subjected to high temperature processing after its formation. Of course, there can be other variations, modifications, and alternatives.

FIG. **8** is a simplified diagram illustrating a scribe and break operation according to one or more embodiments. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. After the n-contact is formed, the substrates are demounted from the sapphire carrier wafer and cleaned in acetone and isopropyl alcohol according to a specific embodiment. The substrates are then mounted onto vinyl tape for the scribe and break process depending upon the embodiment. In a preferred embodiment, the tape does not leave any residue on the laser bars, which are substantially free from such residues, which are often polymeric in nature or particulates.

Next, the method includes one or more scribing processes. In a specific embodiment, the method includes subjecting the substrates to a laser for pattern formation. In a preferred embodiment, the pattern is configured for the formation of a pair of facets for one or more ridge lasers. In a preferred embodiment, the pair of facets face each other and are in parallel alignment with each other. In a preferred embodiment, the method uses a UV (355 nm) laser to scribe the laser bars. In a specific embodiment, the laser is configured on a system, which allows for accurate scribe lines configured in one or more different patterns and profiles. In one or more embodiments, the scribing can be performed on the backside, frontside, or both depending upon the application. Of course, there can be other variations, modifications, and alternatives.

In a specific embodiment, the method uses backside scribing or the like. With backside scribing, the method preferably forms a continuous line scribe that is perpendicular to the laser bars on the backside of the GaN substrate. In a specific embodiment, the scribe is generally 15-20 um deep or other suitable depth. Preferably, backside scribing can be advantageous. That is, the scribe process does not depend on the pitch of the laser bars or other like pattern. Accordingly, backside scribing can lead to a higher density of laser bars on each substrate according to a preferred embodiment. In a specific embodiment, backside scribing, however, may lead to residue from the tape on one or more of the facets. In a specific embodiment, backside scribe often requires that the substrates face down on the tape. With frontside scribing, the backside of the substrate is in contact with the tape. Of course, there can be other variations, modifications, and alternatives.

In a preferred embodiment, the present method uses frontside scribing, which facilitates formation of clean facets. In a specific embodiment, the frontside scribing process is preferably used. In a specific embodiment, the method includes a scribe pattern to produce straight cleaves with minimal facet roughness or other imperfections. Further details of scribing are provided below.

Scribe Pattern: The pitch of the laser mask is about 200 um, but can be others. The method uses a 170 um scribe with a 30 um dash for the 200 um pitch. In a preferred embodiment, the scribe length is maximized or increased while maintaining the heat affected zone of the laser away from the laser ridge, which is sensitive to heat.

Scribe Profile: A saw tooth profile generally produces minimal facet roughness. It is believed that the saw tooth profile shape creates a very high stress concentration in the material, which causes the cleave to propogate much easier and/or more efficiently.

In a specific embodiment, the present method provides for a scribe suitable for fabrication of the present laser devices. As an example, FIG. **9** illustrates cross-sections of substrate materials associated with (1) a backside scribe process; and (2) a frontside scribe process. Of course, there can be other variations, modifications, and alternatives.

Referring now to FIG. **10**, the method includes a breaking process to form a plurality of bar structures. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. After the GaN substrates are scribed, the method uses a breaker to cleave the substrates into bars. In a specific embodiment, the breaker has a metal support that has a gap spacing of 900 um. The substrate is positioned over the support so that the scribe line is in the centered. A suitably sharp ceramic blade, then applies pressure directly on the scribe line causing the substrate to cleave along the scribe line.

FIG. **11** is a simplified diagram illustrating a stacking and coating process according to one or more embodiments. Again, this diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. After cleaving, the bars are stacked in a fixture that allows for coating the front facet and back facet, which are in parallel alignment with each other and facing each other. The front facet coating films can be selected from any suitable low reflectance design (AR design). The AR design includes a quarterwave coating of Al_2O_3 capped with a thin layer of HfO_2 according to a specific embodiment. The Al_2O_3 coating is a robust dielectric, and HfO_2 is dense, which helps environmentally passivate and tune the reflectance of the front facet. These coating films are preferably deposited by e beam evaporation. In a specific embodiment, the back facet is coated with a high reflectance HR design. The HR design includes several quarterwave pairs of SiO_2/HfO_2. In a specific embodiment, roughly 6-7 pairs may be used to achieve a reflectance over 99%. Of course, there can be other variations, modifications, and alternatives.

In a preferred embodiment, the method uses a suitable deposition system configured for deposition of each of the facets without breaking vacuum. The deposition system includes a dome structure with sufficient height and spatial volume. The system allows for the plurality of bars configured in a fixture to be flipped from one side to another side and to expose the back facet and the front facet according to a specific embodiment. In a preferred embodiment, the method allows for first deposition of the back facet, reconfiguring the bar fixture to expose the front facet, and second deposition of the front facet without breaking vacuum. In a preferred embodiment, the method allows for deposition of one or more films on front and back without breaking vacuum to save time and improve efficiency. Other embodiments can break vacuum. Of course, there can be other variations, modifications, and alternatives.

FIG. **12** illustrates a method directed to singulate bars into a plurality of die according to a specific embodiment. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. After the facets of the bars have been coated, the method includes testing the laser devices in bar form prior to die singulation. In a specific embodiment, the method singulates the bars by performing a scribe and break process (similar to the facet cleave). Preferably, the method forms a shallow continuous line scribe on the top side of the laser bar according to a specific embodiment. The width of each die is about 200 um, which may reduce the support gap to 300 um or so. After the bars have been cleaved into individual die, the tape is expanded and each of the die is picked off of the tape. Next, the method performs a packing operation for each of the die according to one or more embodiments.

EXAMPLE

FIG. **13** is a simplified diagram illustrating a laser device according to one or more examples of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives. In this example, the optical device includes a gallium nitride substrate member having a nonpolar crystalline surface region characterized by an orientation of about 1 degree towards (000-1) and less than about 0.3 degrees towards (11-20). The bulk nitride GaN substrate comprises nitrogen and has a surface dislocation density below 1E-6 cm^{-2} and a surface roughness of less than 0.2 nm.

The device has a laser stripe region formed overlying a portion of the nonpolar crystalline orientation surface region. The laser stripe region is characterized by a cavity orientation is substantially parallel to the c-direction and has a first end and a second end. The device has a first cleaved c-face facet provided on the first end of the laser stripe region and a second cleaved c-face facet provided on the second end of the laser stripe region. The first cleaved c-facet is substantially parallel with the second cleaved c-facet. Mirror surfaces are formed on each of the cleaved surfaces. The first cleaved c-facet comprises a first mirror surface. The first mirror surface is provided by a scribing and breaking process such as the one described herein. The first mirror surface comprises a reflective coating, which is alumina and hafnia. The second cleaved c-facet comprises a second mirror surface. The second mirror surface is provided by a scribing and breaking process such as the one described herein. The second mirror surface comprises a reflective coating, such as silicon dioxide and hafnia. In a specific embodiment, the laser stripe has a length and width. The length is 400-1000 μm and the width is 1.4-4 μm. The width is substantially constant in dimension.

As shown, the device is also characterized by a spontaneously emitted light is polarized in substantially perpendicular to the c-direction. That is, the device performs as a laser. The spontaneously emitted light is characterized by a polarization ratio perpendicular to the c-direction. As also shown, the spontaneously emitted light characterized by a wavelength of about 405 nanometers to yield blue-violet emission. Other parameters included:

Power_{CW}>350 mW;

I_{th}<35 mA;

SE>1.0 W/A; and

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As shown, the graph illustrates a power and current relationship for the subject laser device at about 25 Degrees Celsius. Additionally, the wavelength is indicated at about 405 nanometers for the subject laser device. Again, the present device is merely an illustration and should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, modifications, and alternatives.

In other embodiments, the present invention includes a device and method configured on other gallium and nitrogen containing substrate orientations. In a specific embodiment, the gallium and nitrogen containing substrate is configured on a family of planes including a {20-21} crystal orientation. In a specific embodiment, {20-21} is 14.9 degrees off of the m-plane towards the c-plane (0001). As an example, the miscut or off-cut angle is +/−17 degrees from the m-plane towards c-plane or alternatively at about the {20-21} crystal orientation plane. As another example, the present device includes a laser stripe oriented in a projection of the c-direction, which is perpendicular to the a-direction (or alternatively on the m-plane, it is configured in the c-direction). In one or more embodiments, the cleaved facet would be the gallium and nitrogen containing face (e.g., GaN face) that is +/−5 degrees from a direction orthogonal to the projection of the c-direction (or alternatively, for the m-plane laser, it is the c-face). Of course, there can be other variations, modifications, and alternatives.

While the above is a full description of the specific embodiments, various modifications, alternative constructions and equivalents may be used. Therefore, the above description and illustrations should not be taken as limiting the scope of the present invention which is defined by the appended claims.

What is claimed is:

1. An optical device comprising:

a gallium and nitrogen containing substrate member having an m-plane nonpolar crystalline surface region characterized by an off-cut orientation of about −2 degrees to about 2 degrees toward (000-1) and less than about 0.5 degrees toward (11-20), the off-cut orientation not inclusive of zero degrees toward (000-1);

a laser stripe region formed overlying a portion of the m-plane nonpolar crystalline surface region, the laser stripe region being characterized by a cavity orientation substantially parallel to a c-direction, the laser stripe region having a first end and a second end;

a first cleaved c-face facet provided on the first end of the laser stripe region, the first cleaved c-face facet comprising a first mirror surface, the first cleaved c-face facet having first laser scribed regions extending intermittently along a first upper edge of the first cleaved c-face facet to provide a first saw tooth profile, wherein each of the first laser scribed regions forms a tooth of the first saw tooth profile, each of the first laser scribed regions is spaced from adjacent ones of the first laser scribed regions by smooth surfaces of the first cleaved c-face facet, and a depth that the first laser scribed regions extend downward from the first upper edge toward the m-plane nonpolar crystalline surface region varies across the first cleaved c-face facet; and

a second cleaved c-face facet provided on the second end of the laser stripe region, the second cleaved c-face facet comprising a second mirror surface, the second cleaved c-face facet having second laser scribed regions extending intermittently along a second upper edge of the second cleaved c-face facet to provide a second saw tooth profile, wherein each of the second laser scribed regions forms a tooth of the second saw tooth profile, each of the second laser scribed regions is spaced from adjacent ones of the second laser scribed regions by smooth surfaces of the second cleaved c-face facet, and a depth that the second laser scribed regions extend downward from the second upper edge toward the m-plane nonpolar crystalline surface region varies across the second cleaved c-face facet.

2. The device of claim **1** wherein the first cleaved c-face facet is substantially parallel with the second cleaved c-face facet.

3. The device of claim **1** wherein the first mirror surface is provided by a scribing and breaking process from a front side of the gallium and nitrogen containing substrate member.

4. The device of claim **3** wherein the first mirror surface comprises a coating to modify the reflection characteristic.

5. The device of claim **4** wherein the coating is selected from silicon dioxide, hafnia, titania, tantalum pentoxide, and Al_2O_3.

6. The device of claim **1** wherein the second mirror surface is provided by a scribing and breaking process.

7. The device of claim **1** wherein the second mirror surface comprises a coating to modify the reflection characteristic.

8. The device of claim **7** wherein the coating is selected from silicon dioxide, hafnia, titania, tantalum pentoxide, and Al_2O_3.

9. The device of claim **1** wherein the laser stripe region has a length ranging from about 100 microns to about 2000 microns.

10. The device of claim **1** wherein the laser stripe region has a width ranging from about 1 micron to about 15 microns.

11. The device of claim **1** further comprising a spontaneously emitted light polarized perpendicular to the c-direction.

12. The device of claim **1** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 385 to about 420 nanometers.

13. The device of claim **1** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 420 to about 460 nanometers.

14. The device of claim **1** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 460 to about 500 nanometers.

15. The device of claim **1** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 500 to about 550 nanometers.

16. The device of claim **1** wherein the laser stripe is provided by an etching process selected from dry etching and wet etching.

17. The device of claim **1** further comprising an n-type metal region overlying a backside of the gallium and nitrogen containing substrate member and a p-type metal region overlying an upper portion of the laser stripe region.

18. The device of claim **1** wherein the laser stripe region comprises an overlying dielectric layer exposing an upper portion of the laser stripe region.

19. The device of claim **1** further comprising an n-type gallium nitride region overlying the surface region, an active region overlying the n-type gallium nitride region, and the laser stripe region overlying the active region.

20. The device of claim **19** wherein the active region comprises one to twenty quantum well regions, the one to twenty quantum well regions characterized by a thickness of 10 Angstroms to about 40 Angstroms.

21. The device of claim **19** wherein the active region comprises one to twenty quantum well regions, the one to twenty quantum well regions characterized by a thickness of 40 Angstroms to about 80 Angstroms.

22. The device of claim **19** further comprising an electron blocking region, wherein the electron blocking region overlies the active region.

23. The device of claim **19** further comprising a separate confinement hetero-structure, wherein the separate confinement hetero-structure overlies the n-type gallium nitride region.

24. A method for forming an optical device comprising:

providing a gallium nitride substrate member having an m-plane nonpolar crystalline surface region characterized by an orientation of about −2 degrees to about 2 degrees towards (000-1) and less than about 0.5 degrees towards (11-20), the off-cut orientation not inclusive of zero degrees toward (000-1);

forming a laser stripe region overlying a portion of the m-plane nonpolar crystalline surface region, the laser stripe region being characterized by a cavity orientation substantially parallel to a c-direction, the laser stripe region having a first end and a second end and having a top and a bottom, the bottom being closer to the m-plane nonpolar crystalline surface region than the top; and

forming a pair of cleaved facets including a first cleaved c-face facet provided on the first end of the laser stripe region and a second cleaved c-face facet provided on the second end of the laser stripe region, the first cleaved c-face facet comprising a first mirror surface, the first cleaved c-face facet having first laser scribed regions extending intermittently along a first upper edge of the first cleaved c-face facet to provide a first saw tooth profile, wherein each of the first laser scribed regions forms a tooth of the first saw tooth profile, each of the first laser scribed regions is spaced from adjacent ones of the first laser scribed regions by smooth surfaces of the first cleaved c-face facet, and a depth that the first laser scribed regions extend downward from the first upper edge toward the m-plane nonpolar crystalline surface region varies across the first cleaved c-face facet, and the second cleaved c-face facet comprising a second mirror surface, the second cleaved c-face facet having second laser scribed regions extending intermittently along a second upper edge of the second cleaved c-face facet to provide a second saw tooth profile, wherein each of the second laser scribed regions forms a tooth of the second saw tooth profile, each of the second laser scribed regions is spaced from adjacent ones of the second laser scribed regions by smooth surfaces of the second cleaved c-face facet, and a depth that the second laser scribed regions extend downward from the second upper edge toward the m-plane nonpolar crystalline surface region varies across the second cleaved c-face facet.

25. The method of claim **24** wherein the forming of the pair of cleaved facets comprises separately forming of the first cleaved c-face facet and forming the second cleaved c-face facet.

26. The method of claim **24** further comprising coating the first cleaved c-face facet and coating the second c-face facet.

27. The method of claim **24** wherein the pair of cleaved facets is formed before a singulating process.

28. An optical device comprising:

a gallium and nitrogen containing substrate member having a {20-21} crystalline surface region characterized by an off-cut orientation of −8 degrees to −2 degrees or 2 degrees to 8 degrees toward a c-plane;

a laser stripe region formed overlying a portion of the crystalline surface region, the laser stripe region having a first end and a second end;

a first cleaved facet provided on the first end of the laser stripe region, the first cleaved facet comprising a first mirror surface, the first cleaved facet having first laser scribed regions extending intermittently along a first upper edge of the first cleaved c-face facet to provide a first saw tooth profile, wherein each of the first laser scribed regions forms a tooth of the first saw tooth profile, each of the first laser scribed regions is spaced from adjacent ones of the first laser scribed regions by smooth surfaces of the first cleaved c-face facet, and a depth that the first laser scribed regions extend downward from the first upper edge toward the m-plane nonpolar crystalline surface region varies across of the first cleaved facet; and

a second cleaved facet provided on the second end of the laser stripe region, the second cleaved facet comprising a second mirror surface, the second cleaved facet having second laser scribed regions extending intermittently along a second upper edge of the second cleaved c-face facet to provide a second saw tooth profile, wherein each of the second laser scribed regions forms a tooth of the second saw tooth profile, each of the second laser scribed regions is spaced from adjacent ones of the second laser scribed regions by smooth surfaces of the second cleaved c-face facet, and a depth that the second laser scribed regions extend downward from the second upper edge toward the m-plane nonpolar crystalline surface region varies across the second cleaved facet.

29. The device of claim **28** wherein the first cleaved facet is substantially parallel with the second cleaved facet.

30. The device of claim **28** wherein the first mirror surface is provided by a scribing and breaking process from of the gallium and nitrogen containing substrate member.

31. The device of claim **28** wherein the first mirror surface comprises a coating to modify the reflection characteristic.

32. The device of claim **31** wherein the coating is selected from silicon dioxide, hafnia, titania, tantalum pentoxide, and Al_2O_3.

33. The device of claim **28** wherein the second mirror surface is provided by a scribing and breaking process.

34. The device of claim **28** wherein the second mirror surface comprises a coating to modify the reflection characteristic.

35. The device of claim **34** wherein the reflective coating is selected from silicon dioxide, hafnia, titania, tantalum pentoxide, and Al_2O_3.

36. The device of claim **28** wherein the laser stripe region has a length ranging from about 100 microns to about 2000 microns.

37. The device of claim **28** wherein the laser stripe region has a width ranging from about 1 micron to about 15 microns.

38. The device of claim **28** further comprising a spontaneously emitted light is polarized perpendicular to the c-direction.

39. The device of claim **28** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 385 to about 420 nanometers.

40. The device of claim **28** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 420 to about 460 nanometers.

41. The device of claim **28** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 460 to about 500 nanometers.

42. The device of claim **28** further comprising a spontaneously emitted light characterized by a wavelength ranging from about 500 to about 550 nanometers.

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